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Effect of Bulk Density on Frost Heaving of Six Soils in Arizona

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For all soils and depths, frost heaving increased with bulk density. All soils had essentially the same water content when they started to freeze, which indicates that, as bulk densities decreased, percentage of pores filled with air increased. At higher bulk densities, capillary flow is probably improved.

Keywords: Frost heaving, soil bulk density, tree seedling mortality.

Frost heaving of tree seedlings is a serious problem in many parts of the world. Areas subject to frost heaving are characterized by below-freezing temperatures, adequate soil water, and susceptible soils. In northern Arizona, frost heaving is a leading cause of ponderosa pine seedling mortality (Larson 1961). Heaving of first-year seedlings is usually more severe than for nursery transplants (Haasis 1923, Schramm 1958).

In 1971 a comprehensive study of frost heaving was begun at Flagstaff to identify susceptible soils and develop control measures. Preliminary field and laboratory observations indicated that frost heaving was related to soil bulk density (fig. 1). As a result, the following study relating frost heaving to bulk density was begun in December 1972.

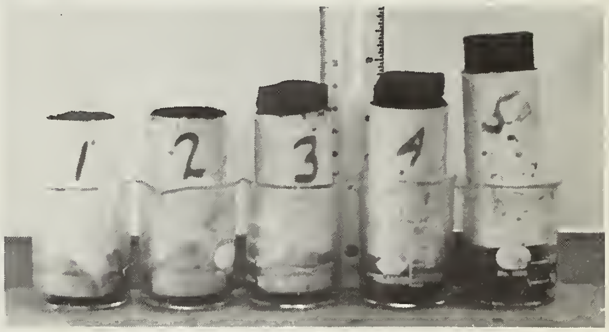

Figure 1.—Example of the relationship between bulk density and frost heaving. Left to right, the bulk densities are: 0.9, 1.0, 1.1, 1.2, and 1.25. Note that the soil has pushed out of the bottom of the cylinders, especially those on the right.

Methods

Soil Collection and Preparation

A review of the literature[3] indicated that frost heaving is closely correlated with soil particle size. As a result, six soils of varying texture were selected for study; all were collected within a 40-mile radius of Flagstaff, at elevations ranging from 3,800 to 7,400 feet elevation (table 1).

Five of the soils were collected from the ponderosa pine zone, while one was collected from a desert-grassland site. At each location four soil samples were collected from each of three soil depths. Depths sampled were: 0-2.5 cm, 2.5-7.6 cm, and 7.6-15.2

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[3]Heidmann, L. J. Forst heaving of tree seedlings: A literature review of causes and possible control. (Manuscript in preparation at Rocky Mt. For. and Range Exp. Stn., Flagstaff, Ariz.)

Table 1.--Bulk density and textural classification[1] for six soils from northern Arizona at three depths

Location and soil depth *(cm)*	Elevation	Bulk density	Sand	Silt	Clay	Organic matter	Textural classification (USDA system)
	Feet			- - - *Percent* - - -			
Tie Park (TP)	7,400						
0 - 2.5		1.21	0	66	34	4.33	Silty clay loam
2.5 - 7.6		1.08	1	66	33	1.93	Silty clay loam
7.6 - 15.2		1.27	0	62	38	1.90	Silty clay loam
Beaverhead Flat (BF)	3,800						
0 - 2.5		1.56	60	30	10	.33	Sandy loam
2.5 - 7.6		1.79	52	34	14	.20	Sandy loam
7.6 - 15.2		1.75	51	32	17	.20	Loam
Fort Valley Experimental Forest--							
S-3 West (S-3W)	7,300						
0 - 2.5		.93	15	68	17	2.27	Silt loam
2.5 - 7.6		.97	13	66	21	3.43	Silt loam
7.6 - 15.2		1.07	9	66	25	1.87	Silt loam
S-3 East (S-3E)	7,300						
0 - 2.5		1.14	16	64	20	2.47	Silt loam
2.5 - 7.6		1.09	15	67	18	1.47	Silt loam
7.6 - 15.2		1.20	10	66	24	.77	Silt loam
Beaver Creek Watershed 14 (W-14)	7,400						
0 - 2.5		1.04	10	61	29	5.20	Silty clay loam
2.5 - 7.6		1.24	3	66	31	6.83	Silty clay loam
7.6 - 15.2		1.32	5	66	29	2.57	Silty clay loam
Kelly Tank (Kelly)	7,200						
0 - 2.5		1.08	63	24	13	2.57	Sandy loam
2.5 - 7.6		1.34	61	26	13	3.73	Sandy loam
7.6 - 15.2		1.50	57	28	15	3.20	Sandy loam

[1]As determined by the hydrometer method.

cm. The four soil samples from each depth and location were mixed together and dried for several weeks. Each soil was then sifted through a 2 mm mesh soil sieve and ovendried at 105° C until a constant weight was reached.

Particle size for each soil and depth was determined by the hydrometer method. Soil bulk densities were determined in the field using the sand cone method (Black 1965).

To determine the minimum bulk density, three cylinders (described under "freezing tests") were filled loosely with soil for each location and depth. The cylinders were agitated slightly to settle the soil, but an effort was made not to compact the soil. The amount of dry soil necessary to fill the cylinders was determined to the nearest 0.1 g. In determining the maximum bulk density, soil cylinders were filled with a small amount of soil at a time. After a small increment of soil had been added to a cylinder, it was tamped with a hardwood dowel. Then another increment of soil was added to the cylinder and tamped. This procedure was repeated until the cylinder was full. The cylinders were soaked in water, after which soil was again added until the maximum amount they could hold was reached. The soil in each cylinder was then ovendried. The ovendry weights of soil for the minimum and maximum bulk densities were calculated to the nearest 0.1 g and averaged to find the amount of soil needed for the mean bulk density.

Freezing Tests

Freezing tests for each soil and depth were conducted at minimum, mean, and maximum bulk densities in a specially constructed plywood freezing chest (Heidmann 1974).

The chest is designed to simulate an open system. Polyvinylchloride (PVC) cylinders 3.3 by 7.6 cm are filled with soil and placed in water until a constant

weight is reached. The cylinders are then placed in a pan of water in the freezing chest. The freezing chest is insulated on the bottom and sides with styrofoam. The water is kept from freezing by a heating tape below the pan. The whole chest is placed in a freezer. Since only the surfaces of the soil samples are exposed, freezing occurs from the surface downward.

After all the soil cylinders had been packed for the various bulk density levels, they were placed in pans of water to soak until a constant weight was reached, about 24 hours. The cylinders were removed from the water, allowed to drain for a few minutes, and weighed to the nearest 0.1 g to determine their water content. The soil cylinders were placed in the freezing chest, which was then put in the freezer. Each freezing test lasted 10 days. The ambient temperature in the freezer at 2.5 cm above the soil surface was maintained at approximately -3° C. The samples were checked every 8 hours to determine onset of freezing. At the conclusion of the test, each cylinder was removed and the amount of frost heaving was measured to the nearest millimeter. The depth of frozen soil was also recorded for each cylinder.

The bulk density freezing tests were replicated four times in randomized blocks, a procedure requiring 216 cylinders. The freezing chest has space for 72 cylinders; consequently four separate trials with 54 cylinders were run.

Results

The soils studied varied considerably (table 1). Field bulk densities ranged from less than 1.00 to 1.79. Sand content ranged from zero to over 60 percent. None of the soils had a high clay content, but all contained a considerable amount of silt. Organic matter content also was quite varied.

The data relating frost heaving (table 2) to bulk density were analyzed by covariance analysis. The

Table 2.--Results of tests on six soils from northern Arizona, by location, depth, and bulk density

Soil depth, and location of soil sample	Frost heaving when bulk density is--			Mean frost heaving for soil depth	Moisture content after soaking when bulk density is--			Moisture, dry weight basis, when bulk density is--			Depth frozen, when bulk density is--		
	Minimum	Mean	Maximum		Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum
	- - - - *mm/day* - - - -				- - - *g* - - -			- - *Percent* - -			- - *mm* - - -		
0 - 2.5 cm:													
TP	1.24	1.52	2.03	1.60	23.0	23.9	22.7	48	43	36	48	52	54
BF	.46	.86	1.12	.81	19.3	17.6	16.4	26	22	19	42	36	42
S-3W	.53	.81	1.70	1.01	29.2	28.6	26.3	70	59	47	50	54	52
S-3E	.72	.76	1.69	1.06	27.1	26.9	25.5	60	52	44	45	47	54
W-14	.76	.68	1.44	.96	24.6	27.0	24.9	60	54	52	47	48	55
Kelly	.56	.79	1.06	.80	23.4	22.3	20.0	40	34	28	45	38	46
2.5 - 7.6 cm:													
TP	.85	.80	2.16	1.27	25.0	24.5	22.3	54	45	35	46	44	54
BF	.66	.94	1.36	.99	20.0	18.9	18.1	30	26	22	44	46	48
S-3W	.58	.80	1.98	1.12	27.2	27.2	25.4	64	54	43	43	48	55
S-3E	.56	.76	1.56	.96	25.1	25.6	23.8	57	47	37	43	46	51
W-14	1.16	.98	1.63	1.26	22.9	24.8	24.2	54	48	40	48	48	55
Kelly	.38	.77	.77	.64	22.1	21.3	20.1	38	33	28	38	38	44
7.6 - 15.2 cm:													
TP	1.06	1.42	1.24	1.24	20.0	21.9	22.3	44	41	37	47	49	46
BF	1.04	1.10	1.78	1.31	21.4	20.6	19.4	34	29	25	46	49	48
S-3W	.74	.84	2.58	1.39	23.2	25.1	23.8	51	46	37	46	46	58
S-3E	.72	.82	2.13	1.22	23.4	23.4	23.0	48	40	34	49	50	59
W-14	.99	1.10	1.61	1.23	22.0	24.9	23.6	50	47	38	48	47	48
Kelly	.48	.83	1.84	1.05	22.3	20.9	18.8	41	32	24	41	35	52
Interaction means:													
TP	1.05	1.25	1.81	1.37									
BF	.72	.97	1.42	1.04									
S-3W	.62	.82	2.09	1.17									
S-3E	.67	.78	1.79	1.08									
W-14	.97	.92	1.56	1.15									
Kelly	.47	.80	1.22	.83									

main effect of bulk density was significant at the 0.01 level. Soil types were significantly different (0.01 level) with the main difference due to Kelly and TP (0.83 mm vs 1.37 mm) (table 2). None of the interactions were large. The interaction between depth and bulk density was not significant. The largest interaction was between bulk density and soil type (0.05 level) (fig. 2).

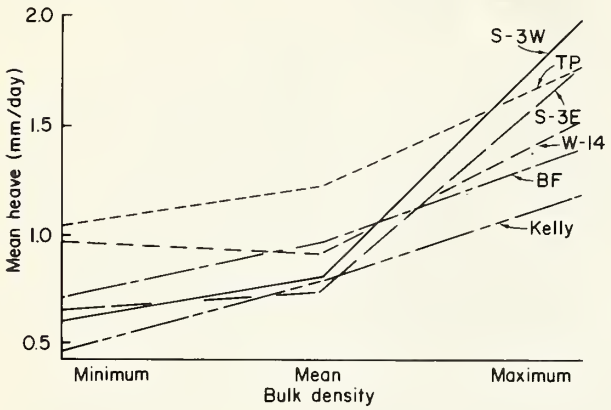

Figure 2.—Interaction diagram showing the relation of soils and bulk density to mean frost heaving per day for six soils in northern Arizona.

The general trend was the same for all soils. Bulk density was dominant in its effect on frost heaving, and this dominance was mainly due to the highest bulk density level.

The total water content in each soil sample before freezing was essentially the same (table 2), which indicates that some of the pores in samples at the lower density levels are filled with air, possibly due to lower capillarity. The soil frost depth was greater at the maximum bulk density levels (table 2).

Discussion

Frost heaving results from the flow of water through the soil to a freezing front where layers of ice are formed (Taber 1929). This movement of water is sometimes referred to as segregation, and is related to negative water pressure (or tension) and permeability. In a heavy clay soil, permeability rates are generally low and water tensions can be high. In a coarse sand, permeability rates are high but soil water tension does not usually develop. According to Penner (1958), a silt soil is ideally suited to frost heaving because soil water tension can be developed and the soil is relatively permeable.

The six soils in this study had fairly high silt contents but were low in clay. In every case when the soils were compacted, frost heaving increased. Compaction most likely improved water flow to the freezing front. Since the total water content of all soils at each bulk density level was essentially the same, soils at the lowest bulk density must have had a considerable amount of pore space filled with air. As a result, capillary flow was restricted and frost heaving was minimal. At mean bulk density levels there were fewer air-filled pores, and capillary flow increased as did frost heaving. At the highest bulk density, the air-filled pores were at a minimum and frost heaving increased greatly. The greater frozen depth in the compacted soils was probably due to a higher rate of heat conduction to the surface. Thorud and Anderson (1969) reported similar findings.

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